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Critical Temperature for the Onset of Spacecraft Charging, The Full Story

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The onset of spacecraft charging at geosynchronous altitudes occurs at a critical value of the space plasma electron temperature for a given spacecraft surface. Observations on LANL satellites show that the onset of charging occurs at a critical temperature in almost every charging event, no matter which satellite, which year and which month. The critical temperature values remain the same no matter in eclipse or sunlight. The satellite observations have confirmed the existence of critical temperature and the order of magnitude of the temperature values. Surface properties in space and in the laboratory are uncertain.

Nomenclature

A	= dipole strength normalized by K
E	= electron energy
k	= Boltzmann's constant
K	= monopole strength
$f(E)$	= electron velocity distribution with velocity expressed in terms of E
r	= distance from the center of a spacecraft
T	= electron temperature
T^*	= critical electron temperature
T_K	= Kappa temperature
δ	= secondary electron coefficient
η	= backscattered electron coefficient
Γ	= gamma function
κ	= kappa parameter
ϕ	= spacecraft surface potential
θ	= sunlight angle (normal at 0°)

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I. Introduction

Spacecraft charging has adverse effects. It may interfere with telemetry signals, disturb scientific measurements onboard, and cause discharges. It may be harmful to the onboard electronics. In severe cases, it may affect the navigation system and even spacecraft survivability.

Spacecraft charging began to receive attention in the 1970s. In 1979, Air Force Geophysics Laboratory and NASA launched the SCATHA satellite dedicated to the study of spacecraft charging. The results obtained from SCATHA invigorated research related to this area. Today, spacecraft charging has become a field of its own.

What causes spacecraft charging? Spacecrafts receiving excess electrons from the ambient plasma charge to negative voltages. Whether in space plasmas or laboratory plasmas, the electron flux exceeds the ion flux by two orders of magnitude because of their mass difference. The flux difference does not guarantee negative voltage charging. This is because, for every incoming electron of energy E , there is a probability $\delta(E)$ of secondary electron emission and a probability $\eta(E)$ of a backscattered electron emission from the surface. In a certain energy range, typically from about 50 to 1500 eV depending on the surface material, $\delta(E)$ exceeds unity. $\eta(E)$ is small ($\ll 1$) at all energies except very near zero energy. The functions $\delta(E)$ and $\eta(E)$ are commonly called secondary electron and backscattered electron yields respectively. Secondary electrons have typically a few eV in energy but a

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backscattered electron may be nearly as energetic as that of the incoming electron. The balance of the incoming and outgoing electron currents determine whether spacecraft charging occurs.

As a remark, charging to positive voltages by outgoing electrons can occur but to a few volts only, which is not important. Secondary electrons, with only a few eV, would be attracted back to the surface if the charging exceeds a few positive volts.

Where does spacecraft charging occur? It occurs mostly in the geosynchronous environment, where the ambient plasma varies in energy from a few eV to several keV sometimes. Most communication and surveillance satellites are there.

II. Onset of Spacecraft Charging

The onset of spacecraft charging at equilibrium is determined by the balance of incoming and outgoing electron fluxes.

$$\int d^3v v_n F(v) = \int d^3v v_n [\delta(E) + \eta(E)] F(v) \quad (1)$$

where $F(v)$ is the ambient electron velocity distribution, v_n is the normal component of the electron velocity, and both sides are definite integrals. In spherical coordinates, one integrates eq(1) over the energy and two angular variables. For normal incidence, the angles on both sides of the equation cancel out. After some simple algebra, one obtains the following equation:

$$\int_0^\infty dEE f(E) = \int_0^\infty dEE [\delta(E) + \eta(E)] f(E) \quad (2)$$

where $f(E)$, which is obtained from $F(v)$ by using $E = (1/2)mv^2$, is the electron distribution with the velocity expressed in terms of energy. For Maxwellian distribution, $f(E)$, is given by

$$f(E) = (n/2mkT)^{3/2} \exp(-E/kT) \quad (3)$$

where n is the electron density, m the electron mass, T the electron temperature, and k the Boltzmann constant. Note that eq(3) is a velocity distribution, and not an energy distribution. In statistical mechanics, the energy distribution is defined differently [1] but we need not use it. Another way to write the onset condition, eq(2), is as follows:

$$\frac{\int_0^\infty dEE f(E) [\delta(E) + \eta(E)]}{\int_0^\infty dEE f(E)} = 1 \quad (4)$$

or simply

$$\langle \delta + \eta \rangle = 1 \quad (5)$$

where $\langle \rangle$ denotes averaging in the sense of eq(4).

For arbitrary angular dependence of electron incidence, one has to integrate over the angles numerically. For simplicity, we will consider normal incidence only in this paper.

Substituting eq(3) into eq(2), one readily sees that the electron density n cancels out on both sides. Thus, the onset of spacecraft charging does not depend on the ambient electron density n . Eq(2) has one unknown, T , only. The solution T^* is the critical temperature.

To solve eq(2), one needs to use explicit formulae of $\delta(E)$ and $\eta(E)$. Using the $\delta(E)$ formula of Ref.[2], and the $\eta(E)$ formula of Ref.[3], one obtains the results in Table 1.

From time to time, there appear in the literature new empirical formulae or new laboratory measurements of $\delta(E)$ and $\eta(E)$. For example, see Figure 1, where the $\delta(E)$ formulae of [2,4,5,6,7] are plotted. Often, a new one claims to be better than all previous ones. They are different from each other. Even the same author may publish different results. We will not side track into this area at this time. The formulae affect the numerical values of the critical temperature. There is no consensus at this time for the best empirical formulae. When a

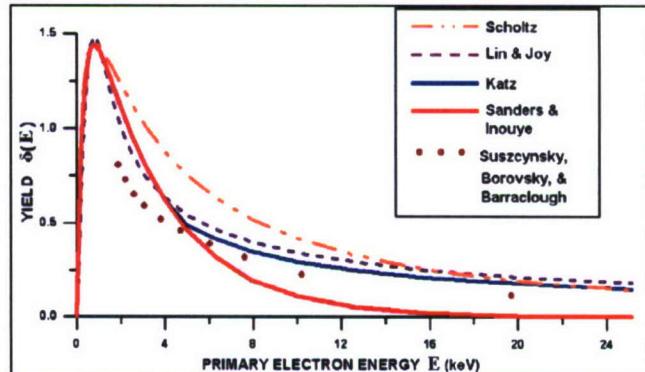


Figure 1. Secondary yield of gold by various authors.

really improved formula of $\delta(E)$ or $\eta(E)$ becomes available, one can always substitute it in eq(2) for updating the numerical value of T^* . When new observational results with known surface materials on a spacecraft are available, one can update the validation of the theoretical values.

There has been a common question about the definitions of temperature. In eq(3), T is the temperature defined in a Maxwellian distribution. In statistical mechanics, temperature can be defined in terms of the moment of the distribution. In a Maxwellian plasma, these two temperatures are identical [Appendix A]. Another common question is whether temperature remains invariant as the charging level varies. The temperature is shown to be invariant [Appendix B].

Table 1 Critical Temperature T^* (keV)

MATERIAL	ISOTROPIC	NORMAL
Mg	0.4	---
Al	0.6	---
Kapton	0.8	0.5
Al Oxide	2.0	1.2
Teflon	2.1	1.4
Cu-Be	2.1	1.4
Glass	2.2	1.4
SiO ₂	2.6	1.7
Silver	2.7	1.2
Mg Oxide	3.6	2.5
Indium Oxide	3.6	2.0
Gold	4.9	2.9
Cu-Be (Activated)	5.3	3.7
MgF ₂	10.9	7.8

Unit of temperature T^* (keV) is for kT .

III. Observational Results

The first evidence (Figure 2) of critical temperature was manifest in the data observed on the ATS-5 satellite [8]. If one plots a straight line through the data points, one can see the intercept at a temperature of about 1.5 keV. At that time, it was before the advent of the theory of critical temperature. The present theory of critical temperature for the onset of spacecraft charging was first presented at an AGU meeting in Philadelphia [9] and, two weeks later, in Europe [10]. At that time, there was no coordinated data of surface charging and electron temperature for verifying the theory [11,12,13].

At the turn of the century, the Los Alamos National Laboratory (LANL) geosynchronous satellite charging data became available. The data show abundant evidence of the existence of critical temperature [14,15]. Below a critical temperature value, charging does not occur. Above it, charging occurs (Figure 3, 4). This phenomenon persists on each of the several LANL satellite on every day, month, season, and year with no exception.

At the present, one still cannot use the LANL data to validate the exact numerical values of critical temperature calculated, because the surface materials are unknown. However, the observed critical temperature values are indeed in the ball park (low keV) of the calculated values for typical surface materials [Table 1].

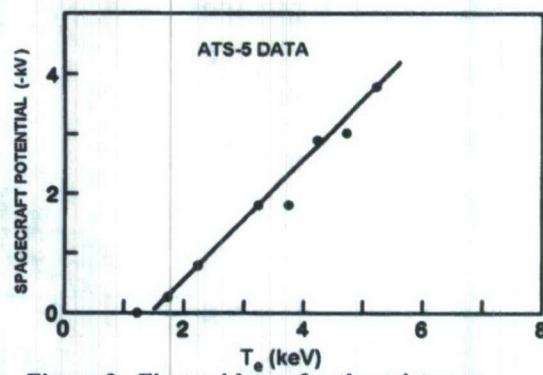


Figure 2. First evidence for the existence of critical temperature. Data [Ref. 8] observed on ATS-5 showed no charging below a finite temperature.

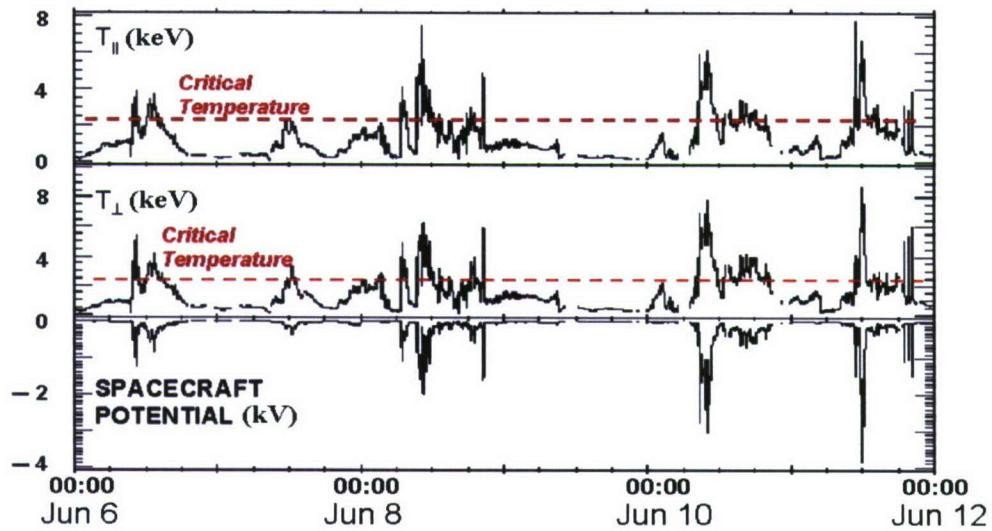


Figure 3. Evidence of critical temperature. Data were taken from Spacecraft LANL-97A. Below the critical temperature, no charging occurs. Above it, the charging level increases with the electron temperature. [Ref.14]

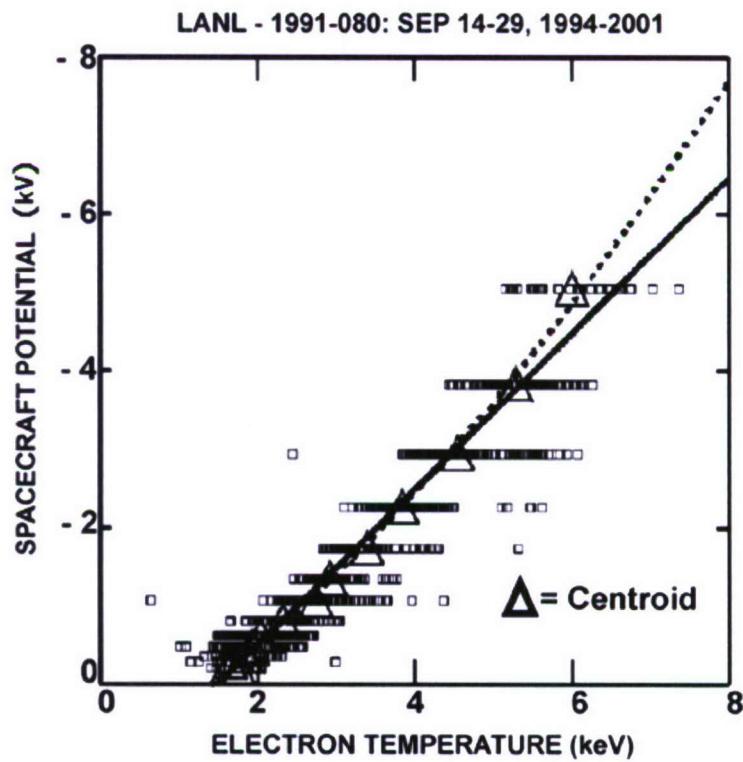


Figure 4. Spacecraft potential and electron temperature measured on Spacecraft LANL-1991-080 during periods 14-29 September 1994-2001. [Ref.15]

IV. Charging in Sunlight

The outgoing photoelectron flux from surfaces exceeds the incoming ambient electron flux. Therefore, charging to negative voltages is impossible for a conducting spacecraft. However, for spacecraft with dielectric surfaces, charging to negative voltages occurs on the shadowed side as if in eclipse. The sunlit side may charge to positive voltages. But, since photoelectrons are of a few eV in energy, any positive charging by photoemission is at most a few V only. The high negative potential of the shaded side wraps around the sunlit side forming a potential barrier, which blocks some photoelectrons from escaping. As a result, a monopole-dipole potential configuration [16] is formed.

$$\phi(\theta, r) = K \left(\frac{1}{r} - \frac{A \cos \theta}{r^2} \right) \quad (6)$$

where K is the monopole strength, r is the distance from the satellite center, A is the dipole strength normalized by K . The angle $\theta = 0^\circ$ is the normal sunlight direction.

For unit radii satellite, the radial distance $r = 1$ at the satellite surface, and $K = \phi(90^\circ, 1)$ equals the monopole potential. The potential barrier is located at r_s , where the potential is the maximum for $\theta = 0^\circ$.

$$\left[\frac{d\phi(0^\circ, r)}{dr} \right]_{r=r_s} = 0 \quad (7)$$

which gives $r_s = 2A$. Therefore, $A > \frac{1}{2}$, otherwise the barrier would be located inside the spacecraft. The barrier height B is given by

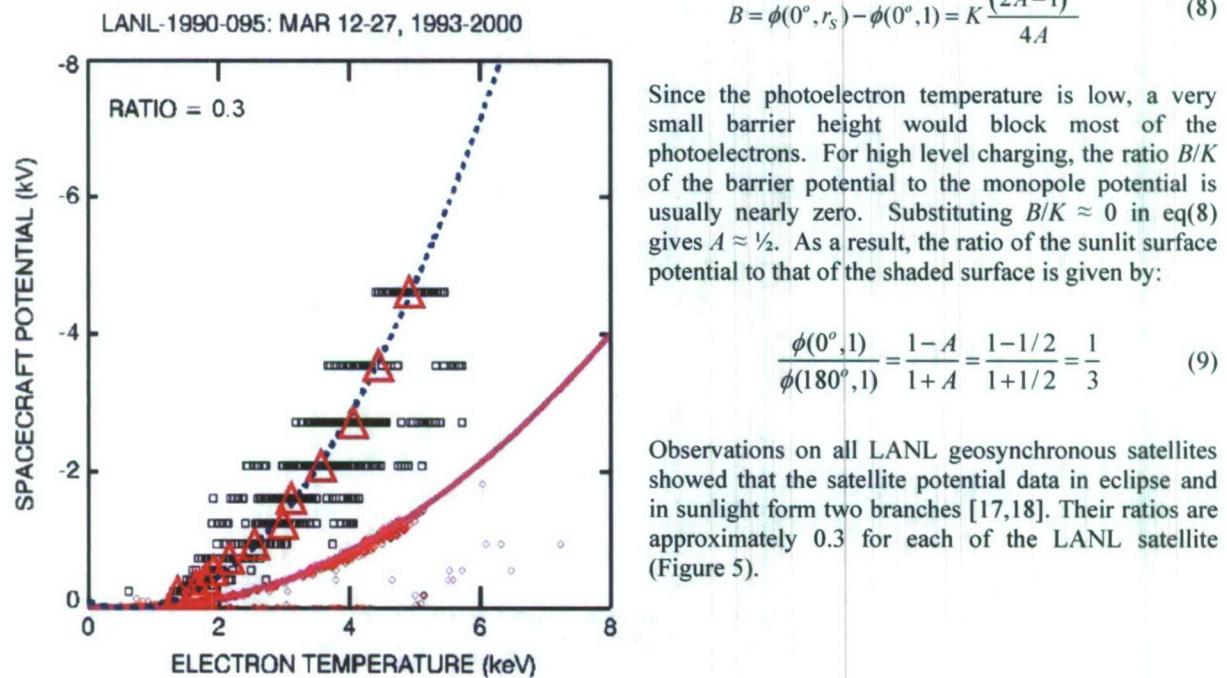


Figure 5. (Upper branch) Charging in eclipse and (lower) in sunlight. The data are quantized because of the discrete flux channels. The centroids of the temperature at every quantized level is shown as triangles. The ratio of the two branches is about 0.3. [Ref.18]

Since the photoelectron temperature is low, a very small barrier height would block most of the photoelectrons. For high level charging, the ratio B/K of the barrier potential to the monopole potential is usually nearly zero. Substituting $B/K \approx 0$ in eq(8) gives $A \approx \frac{1}{2}$. As a result, the ratio of the sunlit surface potential to that of the shaded surface is given by:

$$\frac{\phi(0^\circ, 1)}{\phi(180^\circ, 1)} = \frac{1-A}{1+A} = \frac{1-1/2}{1+1/2} = \frac{1}{3} \quad (9)$$

Observations on all LANL geosynchronous satellites showed that the satellite potential data in eclipse and in sunlight form two branches [17,18]. Their ratios are approximately 0.3 for each of the LANL satellite (Figure 5).

V. Onset of Charging in Kappa Plasma

The kappa distribution is sometimes a good description of the space plasma in non-equilibrium [17,18]. It is of the following form:

$$f_{\kappa}(E) = n \frac{\Gamma(\kappa+1)}{\Gamma(3/2)\Gamma(\kappa-1/2)} \left[\left(\kappa - \frac{3}{2} \right) T_{\kappa} \right]^{\frac{3}{2}} \left[1 + \frac{E}{(\kappa-3/2)T_{\kappa}} \right]^{-(\kappa+1)} \quad (10)$$

where Γ is the gamma function, κ is the kappa parameter, and the kappa temperature T_{κ} is related to the usual temperature T by

$$T_{\kappa} = \frac{\kappa}{(\kappa-3/2)} T \quad (11)$$

Note that $3/2 < \kappa < \infty$. In the limit $\kappa \rightarrow \infty$, one recovers the Maxwellian distribution.

In analog to eq(2), the onset of spacecraft charging in a kappa plasma by using the following current balance equation:

$$\int_0^{\infty} dE E f_{\kappa}(E) = \int_0^{\infty} dE E f_{\kappa}(E) [\delta(E) + \eta(E)] \quad (12)$$

The equation, eq(12), can be solved numerically to obtain the critical kappa temperature T_{κ}^* . The results T_{κ}^* for copper-beryllium (non-activated) as a function of κ is shown in the Figure 6. In the figure, one recovers the Maxwellian result T^* at the asymptote of $\kappa \rightarrow \infty$. If the ambient plasma is nearly Maxwellian, there is little difference between the critical kappa temperature and the usual temperature. Harris [21] fitted some LANL satellite electron distribution data with kappa function instead of Maxwellian. Using the results of Harris [21] for copper-beryllium (non-activated), we have plotted Figure 6. Harris's work showed that there is little difference between kappa and Maxwellian critical temperatures for the onset of spacecraft charging. At the critical temperature (a few keV), the distribution often does not deviate too much from being Maxwellian.

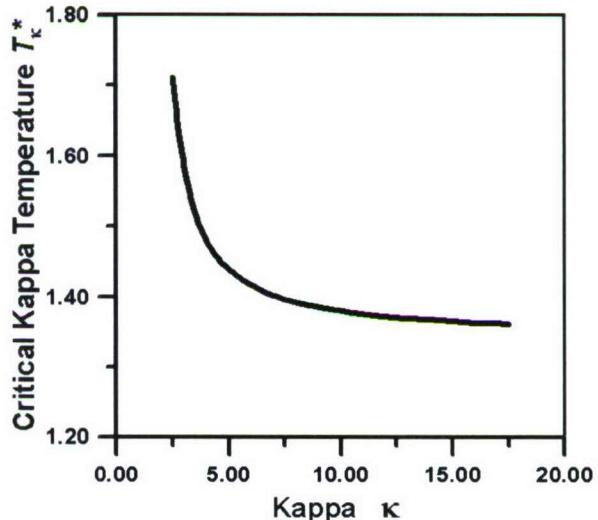


Figure 6. Critical kappa temperature T_{κ}^* for copper-beryllium (non-activated).

VI. Summary and Conclusion

The ATS-5 charging results showed that charging to negative potentials occurred above a critical temperature of the ambient electrons. Above it, the spacecraft potential increased with the electron temperature. The results were obtained before the theory of critical temperature. The theory is based on the balance of incoming and outgoing electron currents. The results of the theory are (1) the onset of spacecraft charging is independent of the ambient electron density, and (2) there exists a critical temperature T^* for the onset of spacecraft charging. The calculated values of T^* for typical spacecraft materials are about a few keV. The voltage configuration around a non-conducting spacecraft charging in sunlight resembles a monopole-dipole. The theoretical results show that the ratio of the potentials in sunlight and in eclipse is about 1/3. All of the above theoretical features appear to be supported well by the LANL results.

However, one still can not use the LANL data to validate the results numerically because the surface materials are unknown, even though the existence of T^* is persistent throughout the data available of all years. The laboratory measurements and empirical results of secondary and backscattered emissions are also different in different papers by different authors. Even an author may publish different measurements and formulae at different time. This problem is well worthy for further studies. When better laboratory data of secondary and backscattered yields are available, one can substitute them in eq(4) for updating the theoretical critical temperature values. Likewise, when new space measurements with known surface materials are available, one can update the validation of the theoretical values.

Finally, if the ambient plasma deviates from being Maxwellian, the results would be different. For a double Maxwellian plasma, the densities can not be neglected [13,22]. One can plot parametric domains delineating the areas of negative charging, positive charging, and triple-root charging [13,22]. For a kappa plasma, the thesis of Harris [21] showed that the onset of charging on the LANL satellites occurred at a critical kappa temperature very near the critical Maxwellian temperature. At high temperatures, well above the critical temperature, the kappa distribution deviates significantly from being Maxwellian.

There is much more for further studies. Imagine an island of knowledge in a sea of unknown. "The more one knows, the longer is the perimeter of the unknown."

Appendix A. Definition of Temperature

This section comments on two temperature definitions. We have defined temperature T as the temperature T in the Maxwellian distribution, eq(3). In statistical mechanics, temperature T_M can also be defined more generally in a moment equation as follows:

$$\frac{3}{2}kT_M = \frac{1}{n} \int_0^\infty d^3v \frac{1}{2}m(v - V)(v - V)f(v) \quad (A1)$$

where V is the mean velocity in a drifting distribution. For an isotropic system, the mean velocity V is zero, and the temperature T_M becomes:

$$\frac{3}{2}kT_M = \frac{1}{2n} \int_0^\infty d^3v m v^2 f(v) \quad (A2)$$

For a Maxwellian distribution, one substitutes eq(3) in eq(A2) and obtains

$$\frac{3}{2}kT_M = \frac{m}{2} \left(\frac{m}{2\pi kT} \right)^{3/2} \int_0^\infty d^3v v^2 \exp\left(-\frac{mv^2}{2kT}\right) \quad (A3)$$

$$= -\frac{m}{2} \left(\frac{m}{2\pi kT} \right)^{3/2} \int_0^\infty d^3v \frac{\partial}{\partial \beta} \exp(-\beta v^2) \quad (A4)$$

where $\beta = m/(2kT)$.

$$\frac{3}{2}kT_M = -\frac{m}{2} \left(\frac{m}{2\pi kT} \right)^{3/2} \frac{\partial}{\partial \beta} \prod \left(\frac{\pi}{\beta} \right)^{1/2} \quad (A5)$$

$$\frac{3}{2}kT_M = \frac{m}{2} \left(\frac{m}{2\pi kT} \right)^{3/2} \left[\pi^{3/2} \frac{3}{2} \left(\frac{2kT}{m} \right)^{5/2} \right] = \frac{3kT}{2} \quad (A6)$$

Since both sides of eqs(A5,A6) are equal, we can equate the two temperatures:

$$T_M = T \quad (A7)$$

We have shown that the two definitions of temperature are identical for a Maxwellian plasma.

Appendix B. Invariance of Temperature at Different Spacecraft Potentials

There has been a question whether the definition of temperature changes as the spacecraft potential changes. This appendix shows that the temperature of the ambient electrons in a Maxwellian distribution is invariant at different spacecraft potentials. Let us define temperature by using the moment equation:

$$\frac{3}{2}kT_M = \frac{1}{n} \int_0^\infty d^3v \frac{1}{2} m(v - V)(v - V) f(v) \quad (B.1)$$

where the notations are as in eq(A1). In the frame of reference in which the drift velocity is zero, eq(B.1) can be written as

$$\frac{3}{2}kT_M = \frac{1}{2n} \int_0^\infty d^3v m v^2 f(v) \quad (B.2)$$

For non-zero (negative) spacecraft potential ϕ , eq(B.2) can be written as

$$\frac{3}{2}kT_\phi = \frac{1}{2} \frac{\int_0^\infty d^3v m v^2 f(v) \exp(-e\phi/kT)}{\int_0^\infty d^3v f(v) \exp(-e\phi/kT)} \quad (B.3)$$

where the Boltzmann factor $\exp(-e\phi/kT)$, multiplied to the Maxwellian distribution $f(v)$, accounts for the electron repulsion. Since the two Boltzmann factors cancel with each other, we can use the same method in Appendix A to show that the two temperatures T_ϕ and T are equal.

Combining Appendix A and B, we have the conclusion:

$$T_M = T = T_\phi \quad (B.4)$$

The temperature defined by means of the Maxwellian distribution is not only the same as that defined by means of the moment equation but also is invariant under electron repulsion at non-zero spacecraft potentials.

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References

- ¹ Mayer, J.E. and M.G. Mayer, *Statistical Mechanics*, John Wiley, NY, 1963.
- ² Sanders, N.L. and G.T. Inouye, "Secondary Emission Effects on Spacecraft Charging: Energy Distribution Consideration," in *Spacecraft Charging Technology 1978*, edited by R.C. Finke and C.P. Pike, pp. 747-755, AFGL, Hanscom AFB., Massachusetts, 1978. NASA-2071, ADA ADA-084626.
- ³ Prokopenko, S.M. and Laframboise J.G.L., "High Voltage Differential Charging of Geostationary Spacecraft," *J. Geophys. Res.*, Vol. 85, No.A8, 1980, pp.4125-4131.
- ⁴ Scholtz, J. J., Dijkkamp, D., and Schmitz, R.W. A., "Secondary Electron Emission Properties," *Philips Journal of Research*, 50, no. 3-4, 1996, pp.375-389.
- ⁵ Lin, Y. and D.G. Joy, "A new examination of secondary electron yield data", *Surf. Interface Anal.*, Vol.37, 2005,

pp.895-900.

- ⁶ Katz, I., M. Mandell, G. Jongeward and M.S. Gussenhoven, "The importance of accurate secondary electron yields in modeling spacecraft charging," *J. Geophys. Res.*, Vol.91, No. A12, 1986, pp.13739-13744.
- ⁷ Suszcynsky, D.M., J.E. Borovsky and C.K. Goertz, "secondary electron yields of solar system ice", *J. Geophys. Res.*, No.E2, 1992, pp.2611-2619.
- ⁸ Rubin, A., Garrett, H.B., and Wendel, A.H., "Spacecraft Charging on ATS-5," Air Force Geophysics Laboratory, AFGL-TR-80-0168, 1980, ADA-090-508.
- ⁹ Lai, S.T., Gussenhoven, M.S. and Cohen, H.A., "Energy Range of Ambient Electrons Responsible for Spacecraft Charging", *EOS Trans. Am. Geophys. U.*, Vol.63, No.18, 1982, p.421.
- ¹⁰ Laframboise, J.G., Godard R. and Kamitsuma M., "Multiple Floating Potentials, Threshold Temperature Effects, and Barrier Effects in High Voltage Charging of Exposed Surfaces on Spacecraft," in *Proceedings of International Symposium on Spacecraft Materials in Space Environment*, Toulouse, France, 1982, pp.269-275.
- ¹¹ Lai, S.T., Gussenhoven, M.S., and Cohen, H.A., "The Concepts of Critical Temperature and Energy Cutoff of Ambient Electrons in High Voltage Charging of Spacecraft," in *Proceedings of the 17th ESLAB Symposium*, edited by D.Guyenne and J.H. A. Pedersen, European Space Agency, Noordwijk, The Netherlands, 1983, pp. 169-175.
- ¹² Laframboise, J.G. and Kamitsuma, M., "The Threshold Temperature Effect in High Voltage Spacecraft Charging," in *Proceedings of Air Force Geophysics Workshop on Natural Charging of Large Space structures in Near Earth Polar Orbit*, AFRL-TR-83-0046, ADA-134-894,1983, pp .293-308.
- ¹³ Lai, S.T., "Spacecraft Charging Thresholds in Single and Double Maxwellian Space Environments," *IEEE Trans. Nucl. Sci.*, Vol.19, 1991, pp.1629-1634.
- ¹⁴ Lai, S.T. and D. Della-Rose, "Spacecraft charging at geosynchronous altitudes: New evidence of existence of critical temperature," *J. Spacecraft & Rockets*, Vol.38, 2001, pp.922-928.
- ¹⁵ Lai, S.T. and M. Tautz, "High-level spacecraft charging in eclipse at geosynchronous altitudes : A statistical study," *J. Geophys. Res.*, Vol.111, A09201, doi:10.1029/2004JA010733, 2006, pp.1-8.
- ¹⁶ Besse, A.L. and A.G. Rubin, "A simple analysis of spacecraft charging involving blocked photoelectron current," *J. Geophys. Res.*, **85**, 2324-2328, 1980.
- ¹⁷ Lai, S.T. and M. Tautz, "High-level spacecraft charging at geosynchronous altitudes: a statistical study", presented at the 8th Spacecraft Charging Technology Conference, NASA Marshall Space Flight Center, 2003; published in the *Proceedings of the Eight Spacecraft Charging Technology Conference*, NASA/CP-2004-213091, 2004.
- ¹⁸ Lai, S.T. and M. Tautz, "Aspects of spacecraft charging in sunlight," *IEEE Trans. Plasma Sci.*, Vol.34, No.5, doi: 10.1109/TPS.2006.883362, 2006, pp.2053-2061.
- ¹⁹ Vasyliunas, V.M., "A survey of low-energy electrons in the evening sector of the magnetosphere with OGO-1 and OGO-3," *J. Geophys. Res.*, Vol.73, 1968, pp.2839-84.
- ²⁰ Meyer-Vernet, N., "How does the solar wind blow? A simple kinetic model," *Eur. J Phys.*, Vol.20, 1999, pp.167-176.
- ²¹ Harris, J., "Spacecraft charging at geosynchronous altitudes: current balance and critical temperature in a non-Maxwellian plasma," AFIT Thesis, 2003.

²² Lai, S.T., "Theory and observation of triple-root jump in spacecraft charging," *J. Geophys. Res.*, Vol.96, No.A11, 1991, pp.19269-19282.